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ScienceDirect

Energy Procedia 45 (2014) 352 – 361

Energy Procedia

68th Conference of the Italian Thermal Machines Engineering Association, ATI2013

# Energy Savings in the Hydraulic Circuit of Agricultural Tractors.

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**Abstract**

Increasing interest in reducing pollutant emissions and fuel consumption of off-road vehicles has led to research into alternative systems that aim to reduce the power dissipation of the hydraulic circuits equipping such vehicles. This work proposes alternative hydraulic architectures for agricultural tractors in comparison with traditional systems. The alternative circuit architecture uses independent metering valves and electronically controlled variable pump and involves different control strategies. The analysis is performed with reference to the hydraulic circuit and operating conditions of the remote utilities of a medium-sized tractor. A duty cycle for remote utilities is used for the analysis, obtained from experimental measurements on a tractor equipped with a front loader. Traditional and alternative architectures are modelled using a lumped parameter approach. In this way it is demonstrated that considerable energy savings can be achieved using the alternative architectures.


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*Keywords*: Tractor, Hydraulic Circuit, Energy Saving, Variable Displacement Pump, Independent Metering.

## 1. Introduction

This study considers a portion of the hydraulic circuit of a medium-size tractor that is composed by the variable displacement axial piston pump and the remote line with proportional distributors and actuators.

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Selection and peer-review under responsibility of ATI NAZIONALE
doi:10.1016/j.egypro.2014.01.038

The first step of the research is an analysis and assessment of energy dissipation of remote utilities in a standard circuit, which is a typical load sensing multi-actuator system (*L.S.M.A.S.*). Since the need to limit pollutant emissions and fuel consumption by agricultural machines has become more and more pressing in recent years, many researchers and manufacturers have focused their efforts on reducing energy consumption in this kind of system without compromising its functionality and performance. From this point of view, the combined use of simulation tools and experimental testing represents the most promising way to develop alternative solutions characterized by lower energy consumption. Many examples exist in literature, mainly regarding excavators and similar vehicles (see for instance [1, 2, 3, 4]). A complete model of an excavator combining empirical approach and mathematical modelling has been for example developed step by step in [5, 6, 7]; this model, whose behaviour has been opportunely compared with experimental measurements, is used to perform analysis of the vehicle control strategies and of global efficiency. With a similar approach, the authors of this paper are focused on the analysis of the tractor hydraulic circuit. Here, one of the most critical feature is that equipment managed by the tractor can change depending on the operation on field and hence also duty cycles are very different instead, for an excavator, the duty cycle can be considered as "standard". For this reason optimization and energy saving is a much more difficult topic when considering a tractor.

In the kind of system analysed in this work the possibility for energy saving lays on the fact that dissipative distributors are used to manage flows and maintain control of multiple loads. The alternative architecture here studied and compared with the traditional one uses independent metering valves (I.M. valves) instead of single spool distributors. The I.M. valves are electronically controlled by an E.C.U. which can adopt different control strategies. The variable displacement pump can be controlled with a traditional flow compensator or with a dedicated E.C.U. From the perspective of energy analysis this architecture offers potential energy savings compared with a traditional single spool valve architecture. However, this must be verified for a real tractor operation because the amount of energy saved strongly depends on the kind of duty cycle involved in the analysis, the required performance and the expected level of reliability. It is noted that the remote valves circuit can serve a wide range of actuators, depending on the equipment connected to the tractor at any given time, for example a seeder, or a loader or a harrow. The actuators can be either single or double effect cylinder and motors. Standardized duty cycles for this kind of circuit do not currently exist, hence more careful analysis must be dedicated to the experimental measurement of the main hydraulic variables during a tractor work cycle using different equipment. For this purpose, a duty cycle for remote utilities is applied, obtained from experimental measurements on a tractor equipped with a front loader. The adopted duty cycle involves two pairs of linear actuators working together with different loads and requiring different flows. The traditional and alternative architectures are modelled using a lumped parameter approach with particular detail dedicated to the modelling of traditional and independent metering valves, to the variable displacement pump and finally to the definition of the control strategies. A comparison of efficiency of the systems is then made with reference to the front loader duty cycle.

## 2. The Standard Load Sensing Hydraulic System

The circuit implementing remote actuator control is a load sensing multi actuator system designed to manage parallel actuations using a variable displacement pump with flow compensator (Figure 1 on the left); each actuator is operated and controlled through a distribution block similar to the one shown in Figure 1 on the right. The core of the distribution block is represented by the proportional control valve 1. The metered power supplied to a hydraulic actuator corresponds to the degree of opening of the proportional valve. The elements labelled 2 are poppet lock check valves, and valve 3 introduces the local compensation control needed to manage the demands of multiple actuators, while the shuttle valve 4 selects the highest load-sensing piloting signal (*LS*) to be delivered to the pump. As shown by the functional description of the proportional control valve 1, the flow-rate modulation is of the meter-in type, which does not allow proper actuator control in the case of high overrunning loads. Under these particular operating conditions, the low pressure load-sensing signal selected by 4 reduces the pump displacement, hence the system reaction is opposite to the actual need of the remote actuator.

The main advantage of this kind of system is that any excess flow, not directly used by the actuators, is only due to system leakages while a relatively small excess pressure, the pump pressure margin, is introduced to operate the actuator. In the case of more than one actuator operating simultaneously, the pressure compensators corresponding to the lower loaded actuators introduce an additional pressure drop in order to maintain control. With a pressure compensator located before the directional valves, as in the standard system, a strategy has to be developed to contrast the reduction of flow going to the higher loaded user when the flow delivered by the pump saturates.

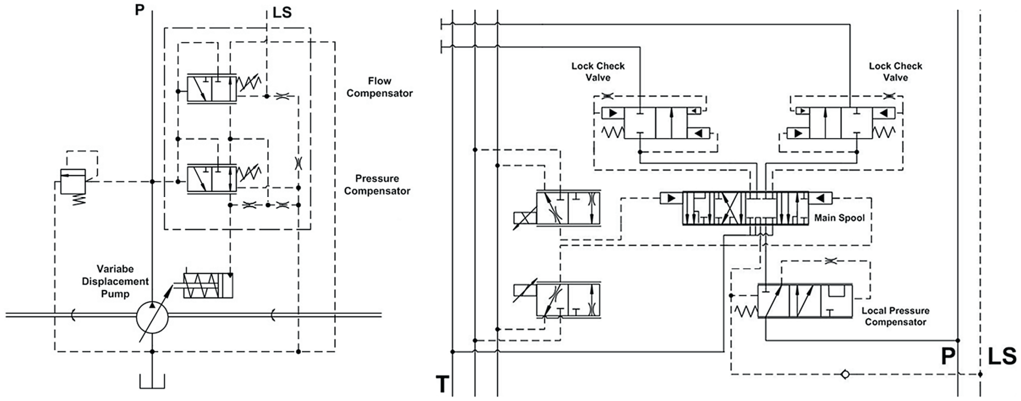


Fig. 1 Hydraulic load sensing power generation system (left), hydraulic scheme of a proportional valve section (right).

## 3. Model Of The Standard Load Sensing Hydraulic System

As a first analytical step, the standard circuit architecture of the *L.S.M.A.S.* was modelled by means of a lumped parameter approach developed in the AMESim environment ([22]), see also [8, 9].

The core of the model is represented by the proportional directional valves which convey the flow to the remote actuators (Figure 2 left side, model in AMESim). In this kind of environment each element represents a function; the elements can be connected and exchange variables following a power port approach. The movement of the main spool is an input of the model (the user control signal), while the movement of the check valves and local compensators are due to the equilibrium of each single spool under the action of pressure and spring effect.

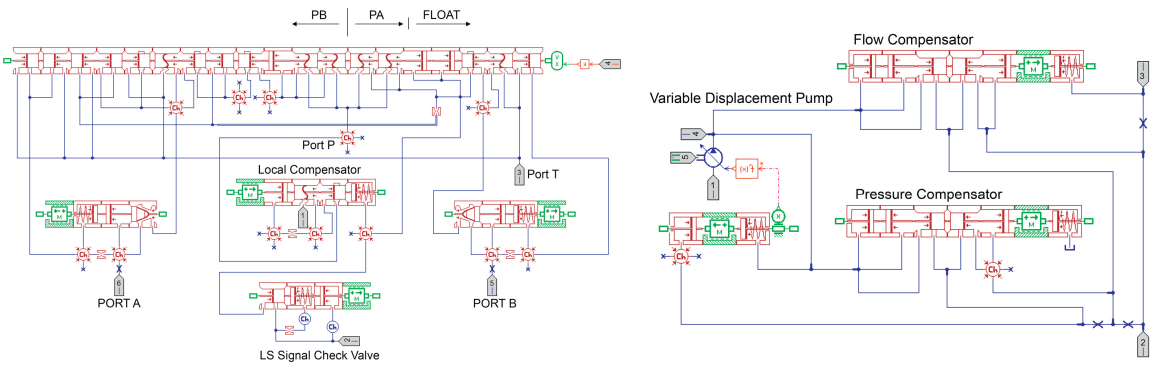


Fig. 2 Valve (left) and hydraulic load sensing power generation system, both modelled in AMESim.

Particular attention was devoted to describing the metering characteristics of the directional valve spools, because they determine the pressure drops across the passages and hence the energy dissipation introduced by the component itself. For the same reason detailed models of the check valves and local pressure compensator were introduced.

Experimental validation of the model was performed by comparing the experimental and numerical pressure drops across different passages in the valve, and comparing the metering characteristics. A hydraulic test rig equipped with a load sensing hydraulic power generator was used to perform the experimental analysis.

The fluid power generator group was modelled as an ideal variable displacement pump with a detailed model of the hydraulic flow compensator, again realised in the AMESim environment (Figure 2, right side). This means that the pump architecture is not considered and the efficiency of this machine must be assigned as an input to the pump model. Conversely, attention is focused on the variable displacement mechanism in order to replicate the operation and dynamic behaviour of a typical load sensing pump. However, the detailed model of the pump, as described in [10, 11], has been already prepared an tested in the system and has given similar results of the simplified model, confirming that the relevant aspect for the aim of this work is the behaviour of the variable displacement mechanism.

At this point it was possible to analyse the energy dissipation introduced by each single component in the hydraulic circuit. This is particularly useful in order to identify possible alternative solutions to minimize energy consumption, by eliminating the most dissipative elements if possible. A steady state analysis [8], developed using variable orifices to connect the user ports A and B of the distributor, identified some critical features: firstly, even when a single user is activated, the presence of the local pressure compensator introduces significant energy dissipation. This can be lowered with an opportune tuning of the spring preload but never completely reduced to zero. Relevant dissipations are introduced at the meter-in section if high flow is requested, while at partial flow the meter-out section also introduces high dissipation because it is partially closed. At high flow, the dissipations through the lock check valves and the quick-release couplings are also relevant. With more than one user active, the dissipation through the local pressure compensator of the lower loaded user is obviously higher.

## 4. Alternative Architectures

The alternative architecture considered is a four spool independent metering system in a typical Wheatstone bridge configuration, with the addition of another valve to allow regeneration when possible (Figure 3). In fact, this solution allows to eliminate the dissipation at the meter out section, to avoid the use of a local compensator because this function can be performed by the main spool opportunely controlled and finally to introduce different control strategies of the single valves in order to manage also overrunning loads, as demonstrated for example in [12, 13, 14, 15].

The block of valves that compose the independent metering architecture is built up virtually using a detailed model of a commercial electro hydraulic poppet valve (EHPV, [21]), which is designed to offer good metering performance over a wide range of operating pressure levels, as well as low leakage and reduced hysteresis [16, 17, 18]. The studied architecture consists of 5 2/2 EHPV: two "free flow" valves on the tank line (A2-B2), two "flow checking" valves on the load lines (A1-B1); one "free flow" bi-directional valve is used on the regeneration line (Figure 3 again). Four pressure transducers measure the pressure on the pump, load ports, and tank and their signals are elaborated in the virtual E.C.U. Different control strategies are introduced for the EHPVs, applying pressure and flow controls and coupling the valves with an electronic controlled pump. A fifth Bi-Directional EHPV can be used to regenerate flow when possible with no need to introduce additional valves or create a constant counter-pressure on the tank. Each type of valve used in the virtual distributor was modelled in the LMS Imagine.Lab AMESim environment.

The front loader duty cycle, described in the [8], was simulated using the traditional and alternative architecture, testing the different control strategies introduced in the last one. The load and flow request transients measured on the instrumented tractor are shown in Figure 4. The utilization of this duty cycle enabled comparison of the performance of the different systems making reference to a real operating condition and evidencing the advantages of adopting independent metering and electronic control of the proportional valves and possibly of the pump.

Particular care was devoted to the modelling of the single EHPV valve ([19]), since the evaluation of energy dissipation in the system may depend on both the steady-state and dynamic characteristics of the metering valves. The distinguishing features of these valves include an internal pressure compensation mechanism that helps considerably to reducing the initial input current required to open the valve. The valve has a three-degrees-of-freedom internal mechanical system with state constraints. The relative displacements of the mechanical components establish the flow rate through the valve. The relationship between the valve flow rate $Q$, pressure difference across the valve $\Delta p$ and the valve flow conductance $K_v$ is defined in the following equation:

$$Q = K_v \cdot \sqrt{\Delta p} \quad (1)$$

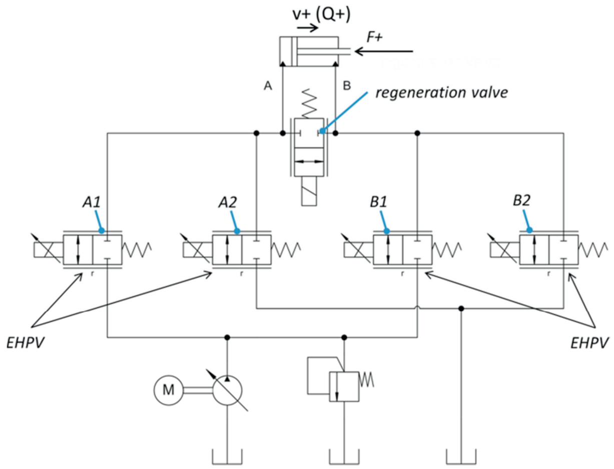


Fig. 3 Alternative Architecture Circuit Layout.

The lumped parameters model considers the mechanical motion equations of the three moving elements, and the influence of the viscous and mechanical friction to which these are subjected.

Once the model was validated for all three types of valve, it was possible to start development of the control strategies for the distributor prototype. Firstly, the definition of a flow-pressure-current map for each type of valve was necessary to allow both direct open loop control and feed-forward closed loop control, in order to improve the performance.

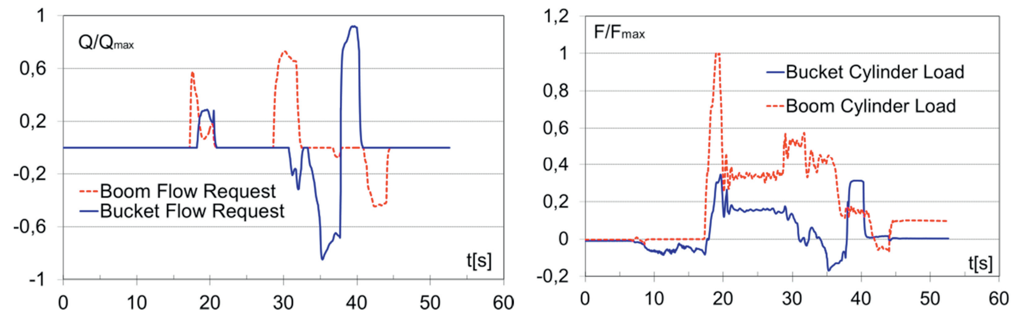


Fig. 4. Non-dimensional flow demand, left, and loads transients, right, on cylinders for boom (rise) of the loader and bucket rotation.

## 5. Control Strategies

Several strategies were developed together with the pump control algorithm. At present, the pump is considered as an ideal component. This means that the pump is always able to supply the required flow with a time delay introduced by a first order filter. The time constant used is 0.05s. Each pressure signal used in the control algorithm is also filtered with a time constant of 0.033s. Some of the most significant control strategies developed are described below.

### 5.1. Valve control

First, the developed virtual distributor is introduced into the circuit to substitute the existing single-spool distributor. The control strategy involves an open loop control of the four main valves as an independent metering architecture. Using the flow request and pressure measurements at the valve ports, the system is able to calculate the current value $I$ to be sent to the valve. Depending on the flow rate $Q_{in}$ and the measured differential pressure $\Delta p$ across the valve, the following logical sequence is developed:

$$Q \rightarrow K_v = Q / \sqrt{\Delta p} \rightarrow I = f(K_v, \Delta p) \tag{2}$$

In particular, four functional conditions are defined both for flow direction (positive or negative flow rate) and type of load (passive or overrunning), with reference to Figure 3:

- Q>0 (positive velocity $v$) and passive loads (positive load $F$); valve A1 controls the meter in-flow rate to be sent to the load while valve B2 is completely opened to reduce the pressure drop on the tank as much as possible.
- Q>0 and overrunning loads; in this case, valve B2 controls the meter out-flow rate while valve A1 is controlled by a PID to avoid cavitation in the inlet chamber of the linear actuator.
- Q<0 and passive loads; valve B1controls the inlet flow rate to the actuator while valve A2 is completely opened to reduce the pressure rise on the tank as far as possible.
- Q<0 and overrunning loads; in this case, valve A2 controls the flow rate of the outlet section of the actuator while valve B1 is controlled by a PID to avoid cavitation in the inlet chamber.

While distinction between positive and negative flow rate request is direct, to discriminate between passive and overrunning loads a force trade-off is required and for this purpose a knowledge of the area ratio of the linear actuator is necessary. The area ratio represents the ratio between the active areas of the cylinder chambers. The selection process is focused on the following equation, where $A_b$ is the active area of the outlet chamber and $A_a$ the active area of the inlet chamber of the cylinder, while $p_b$ and $p_a$ are the correspondent pressure values in the chambers:

$$\begin{aligned} & p_b \cdot \frac{A_b}{A_a} - p_a > \text{overrunning margin (OvM)} \Rightarrow \text{ load is overrunning} \\ & p_b \cdot \frac{A_b}{A_a} - p_a < \text{passive margin (PaM)} \Rightarrow \text{ load is passive} \end{aligned} \tag{3}$$

The values of the margins can be chosen depending on the types of load.

### 5.2. Pump Control

Pump control was achieved in three steps. Firstly, a traditional hydraulic load sensing pump was considered with the difference that the load sensing pressure signal is controlled using two additional EHPVs: one is positioned on the supply line and the other on the tank line. Using an auxiliary E.C.U. (Metering E.C.U.), it is possible to control them with the aim of generating and controlling the load sensing pressure to be sent to the pump compensators for displacement regulation.

Secondly, an electronic control for the hydraulic power supply group was introduced, able to control pump displacement without the use of a hydraulic load sensing line, hence avoiding dissipation along this line. Using the main control algorithm, the pressure load sensing value is sent to the E.C.U. as an electrical signal. The Metering E.C.U. implements a closed loop pressure control able to induce variations in pump displacement with the aim of keeping the supply pressure value equal to the detected pressure load plus a pump margin. An anti-cavitation control ensures that the pressure on the supply line is always higher than 0.05MPa. In this way it is possible to remove the compensator valve of the traditional pump and so to eliminate this source of energy dissipation. The valve control strategy is the same as that described in the previous step.

Finally, dissipation due to the presence of a pump margin, which obliges the system to operate at a higher pressure than that requested by the actuator, can be reduced by direct control on pump displacement. This algorithm is based on the integration of both flow rate control and pressure control. Generally, a flow rate control determines pump displacement, hence the displacement is regulated only on the basis of the sum of the flow requests. When the pressure supply value is higher than a limit value (default is 18MPa), the algorithm will control the pump in an electronic load sensing mode, in order to limit the supply pressure value (anti-saturation control). This algorithm is also able to implement anti-cavitation control when the pressure is lower than 0.05MPa. Moreover, in the virtual model of the independent metering distributor position transducers are introduced to realize a position control, one for each valve. In this way it's possible to carry out a closed loop control, that is more precise than an open loop control and brings the same energy dissipation.

Further improvements are also introduced and focused on valve controls. In particular, a feed-forward with gain scheduling control is introduced for pressure control. Finally, flow control is implemented with both an open loop (OP) and a closed loop (CL) control, assuming the availability of the flow measurement from a flow sensor, or from the swashplate position measured on the pump. The energy dissipations in these two cases are similar but the closed loop control is more precise.

## 6. Results

For each control strategy realized, a simulation was carried out using the front loader duty cycle. The same piston displacements were obtained as a result of the simulation for each control strategy. This shows that the control strategies realized are able to control the actuators of the front loader performing the same duty cycle as the traditional circuit architecture. It also confirms that it is possible to use an optimized algorithm to command both passive and overrunning loads without any loss of control.

Figure 5 shows a comparison of the instantaneous hydraulic power at the delivery of the pump to perform the duty cycle for the different systems described.

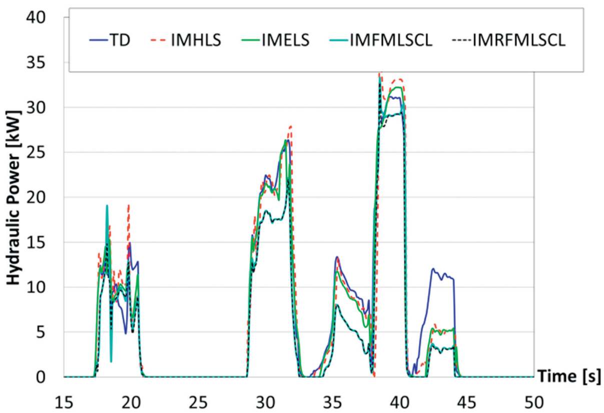


Fig. 5. Instantaneous power at the pump during the duty cycle for the different architectures and control strategies analysed.

The legend refers to the following architectures:

- TD = traditional single spool distributor commonly used on medium-sized power tractors.
- IMHLS = independent control strategy (IM) with electro-hydraulic load sensing for traditional pump control (HLS).
- IMELS = independent control strategy (IM) with electronic load sensing pump control (ELS).

- IMFMLSCL = independent control strategy (IM) with closed loop (CL) flow rate control and direct control of pump displacement (flow matching FL)
- IMRFMLSCL = independent control strategy (IM) with regeneration mode (R), with closed loop (CL) flow rate control and direct control of pump displacement (flow matching FL).

Only closed loop version of the independent metering-direct control of pump displacement systems are shown in figure to improve the understanding; in any case, the difference in power transients between the closed and open loop version are very small.

In some intervals during the cycle, the load condition combined with the flow rate requests make it impossible to obtain a significant reduction in power request in the new architectures compared with the traditional system. For example, in the range 17- 21 seconds, when the tractor is loading the bucket, the pump is under pressure saturation condition and there is no possibility of saving energy in this condition. Furthermore, in this particular duty cycle regeneration plays a minor role because it is only possible for very brief time intervals. Nevertheless, a reduction in the power required to operate the loader characterizes all the other phases of the duty cycle, with relative energy savings from the alternative architectures compared with the traditional load sensing system:

- around 30 s, when the loader is raised and the bucket slightly rotated, but the contemporaneity of the movement of the actuators happens for a very reduced time interval: in this phase the system requires medium-high flow and pressure is high to raise the load. The traditional single spool distributor works with the outlet section partially closed, because it's linked to the partial opening of the inlet section. The independent metering valve leaves the outlet section fully open and operate flow control on the meter-in section. The direct control of pump displacement is slightly more efficient because it saves the pump pressure margin that is used in the load sensing systems and hence meter in losses are very low.
- around 35 s, when the bucket rotates before unloading: in this phase a small load acts on the bucket cylinder, pressure is in a low range and difference within the three systems behaviours is not very high. Again, direct pump displacement control saves the energy that is necessary to generate the pump pressure margin in the load sensing systems.
- 38-40 s, when the bucket unloads: first the user asks for high flow to rotate the bucket and unload then gravity drags the bucket and the load becomes overrunning for a brief time interval. Here energy saving is debatable: it depends strictly on the overrunning margin used to recognize an overrunning load by monitoring the pressures in the two actuator chambers. In the independent metering architectures when an overrunning condition is detected, the control strategy induces a pressure control on the meter in section and a flow control on the meter out section. Thus may be in contrast with energy saving but provides good control over the actuators. Traditional distributors are designed to maintain control only in cases of limited overrunning loads but they may lose control when unexpected high overrunning loads are involved in the duty cycle. A more efficient management of overrunning load offers minor energy savings and avoids cavitation. When the load becomes passive again, the independent metering architectures are more efficient.
- 41- 44 s, the loader is finally lowered, an overrunning load condition is recognized by the alternative architectures at the beginning of the operation, which changes into a passive load condition after a short time: here more efficient management of both situations leads to consistent energy savings in the independent metering architectures compared to traditional systems.

These results confirm that the independent metering approach coupled with electronic control of the pump and a suitable strategy to control the operation of the proportional valves can save a significant amount of energy during a working cycle of the remote actuators of an agricultural tractor.

The efficiency of each control strategy was calculated, starting from the system that uses a traditional distributor and modelled previously. To calculate the efficiency of the system, the following equation was used:

$$\eta = \frac{L_T + L_L}{L_{hp}} \cdot \% \qquad (4)$$

In equation 4, $L_T$ and $L_L$ represent the energy required respectively for the rotation of the bucket and raising of the front loader, while $L_{hp}$ is the hydraulic energy consumption at the pump to perform the entire duty cycle. In

Figure 6 all the systems efficiencies are reported and compared. It is possible to observe step by step that the efficiency increases from 58.8% for the traditional system, to 82.4%, for an independent metering system with regeneration and direct pump displacement control.

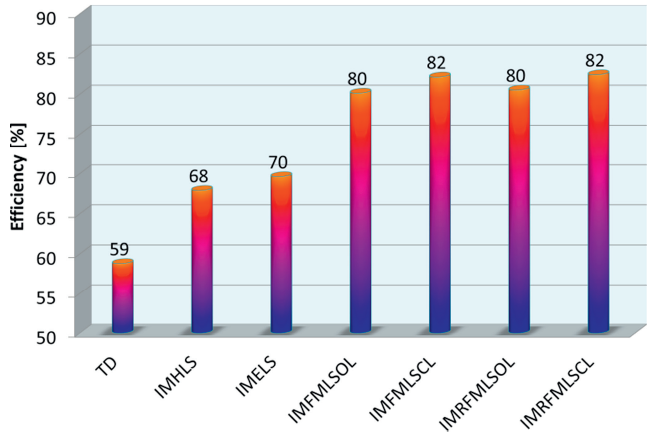


Fig. 6. Efficiency comparison for all the systems analysed.

- TD = traditional single spool distributor commonly used on medium-sized power tractors.
- IMHLS = independent control strategy with electro-hydraulic load sensing for traditional pump control.
- IMELS = independent control strategy with electronic load sensing pump control.
- IMFMLSOL = independent control strategy with open loop flow rate control and flow matching pump control.
- IMFMLSCL = independent control strategy with closed loop flow rate control and flow matching pump control.
- IMRFMLSOL = independent control strategy with regeneration mode, open loop flow rate control and flow matching pump control.
- IMRFMLSCL = independent control strategy with regeneration mode, closed loop flow rate control and flow matching pump control.

## 7. Conclusions And Future Work

The research reported in this paper focuses on an energy analysis of the remote valve hydraulic circuit of a medium-sized agricultural tractor. The circuit is a typical hydraulic load sensing multi actuator application. The main aim of the work was to evaluate energy losses in the standard architecture making reference mainly to an actual duty cycle performed by the tractor. The energy analysis of the circuit highlighted that a certain margin of energy saving can be achieved by eliminating the pressure drops introduced by the meter-out sections of the remote valves and by the pressure compensators acting at the inlets of the lower loaded actuators. Thus, an alternative circuit architecture, based on the well-known independent metering concept, was introduced and modelled, in which single spool remote valves were replaced by independent metering valves. Considering the opportunity to add further functionality and flexibility to the system and the possibility of saving more energy, an electronically controlled variable pump was used. Different control strategies to deal with both the pump displacement and the proportional valves were developed. With the aim of defining a term of comparison between the standard and alternative architectures, an actual duty cycle was performed on a tractor using a front loader. The main result obtained is that, comparing the traditional and alternative architectures, a relevant percentage of energy can be saved due to the combined use of the independent metering concept and electronic control of pump displacement, while preserving the functionality of the system. The authors are working to define further duty cycles [20], with the aim to covering the wide variety of equipment and operations managed by the remote distributors. A critical consideration for the analysis is that in some contexts the remote utilities on agricultural tractors are used for a very limited time compared with the vehicle's life. Thus, the time and cost of introducing new architectures are justified only if there is constant use of the equipment driven by both remote and mid-mount distributors, due to the similarity of these components with circuit architecture. Another critical aspect is that final users often do not know the actuator geometry of agricultural equipment and this kind of knowledge is fundamental for correct operation of the control systems. The authors are currently testing an iterative procedure to overcome this problem: initial operation of the tractor is performed with the sole aim of determining geometry from pressure and flow measurements, which are elaborated by the ECU, controlling the independent valves in order to replicate the behaviour of a traditional distributor with a single spool. Subsequently, the control strategy uses an area ratio estimation to more efficiently control the independent metering valves.

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